Dynamic Testing

Toward a Multiple Exciter Test

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Ensuring that the warfighter is supplied with the safest and most reliable weapon systems is a challenging and often extremely varied process. One critical component in qualifying a system is developing and executing a thorough environmental test sequence representative of the anticipated life cycle of the item to be fielded. Effective development of such a test sequence requires clear communication between program office and test personnel.

This article concentrates on the critical vibration testing element. The field vibration environment may be described as the simultaneous vibration in three translational and three rotational degrees of freedom. Achieving an accurate 6 degree-of-freedom (6-DOF) replication of this environment in a controlled laboratory setting has taken decades of advancements in vibration control and exciter technology. Below are a short historical path of the evolution of the discipline toward multiple exciter/multiple degree-of-freedom (MDOF) testing, an example of an MDOF vibration system and a discussion of benefits of the technology advancements to the acquisition community.

Shock and Vibration—Pre-World War II

The first wide studies of shock and vibrations can be traced to the 1930s when the effects of earthquakes on buildings were being studied in order to improve the behavior of buildings. The work primarily was analytic, using the shock spectrum as defined in research by Belgian-American aeronautical engineer Maurice Anthony Biot. Instrumentation and signal conditioning equipment of the period were in their infancy and test equipment was limited.

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Wide-Ranging Interest in Vibration Testing

The rapid evolution of military hardware during World War II yielded many technological advances such as radar, high-performance vehicles (aircraft, ships, and ground vehicles) and early guided missiles. Coinciding with these advances were new structural and dynamic challenges that led directly to enhanced environmental testing. The combination of higher-performance vehicles generating more severe vibration environments and the use of complex electronics and munitions that are more susceptible to fatigue failure increased the potential for vibration to cause catastrophic failures. During this period, program managers began an initiative to address performance under shock and vibration loading in developing acceptance and qualification programs for increasingly complex products.

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Mechanical Exciters

The World War II and early postwar dynamic test facility consisted largely of mechanical cam-driven excitation systems limited primarily to low-frequency cyclic motion of a circular or elliptical nature. These early mechanical systems were limited in bandwidth, for example a typical machine running circular motion at 300 revolutions per minute (RPM) would correlate to only 5 Hertz (Hz). The constant RPM rotational motion produced a fundamental motion of a periodic (sinusoidal) nature, but also tended to have very high uncontrolled harmonic distortions associated with the drive mechanisms. While they provided a rudimentary vibration environment, the technology was insufficient to address more complex and wider frequency ranges characteristic of the field environments of interest.

Electro-Dynamic and Servo-Hydraulic Exciters

Electro-dynamic exciters, first introduced in 1946, gradually began replacing mechanical exciters. The first generation of such equipment was very inefficient; however, it was quickly realized that such a device could address more complex random environments. Random vibration is defined as non-deterministic, which means that future behavior cannot be predicted precisely. However, it is possible to describe such motion in a statistical sense. Reference criteria for a random vibration environment are presented in the form of an Amplitude Spectral Density (ASD), which essentially is a statistical average of the distribution of energy as a function of frequency. Examples of environments that are characteristically random include a wheeled vehicle running over a rough road, turbulence around high-velocity exhausts or turbulence-induced vibration associated with aircraft or missile flight. Such environments have significant energy content through the 500- to 2,000-Hz range. Clearly, low-frequency sinusoidal motion is not sufficient to characterize such environments. Even though random vibration testing were then feasible, the initial limitation of the time was development of closed-loop control systems to create a controlled and repeatable motion. Also lacking were recognized standards for such tests, an obvious challenge to program managers of the day.

One limitation of electro-dynamic exciters, even those of the modern era, is that the high-force models have a significant footprint. Servo-hydraulic exciters, introduced in the late 1950s, are capable of producing a very high force in a much smaller footprint. While they lack the bandwidth potential of an electrodynamic exciter, development of dual-stage valves made it possible to achieve frequency response on the order of 500 Hz, which is acceptable for defining many environments.

Vibration Standards

As development of electro-dynamic and servo-hydraulic exciters continued to mature and their potential became apparent, standards soon followed. Interestingly, early and modern vibration standards alike tend to be commodity and nationally or regionally based. The first standards were based on sinusoidal motion. The first widely disseminated U.S. military standard for environmental effects that included vibration was the 1962 release of U.S. Military Standard 810 (MIL-STD-810), under custody of the U.S. Air Force. MIL-STD-810, "Environmental Engineering Considerations and Laboratory Tests," is a Department of Defense (DoD) Test Method Standard approved for use by all DoD Service Departments and agencies.

With the onset of the space race and advancing missile technologies in the 1960s, a clear need became apparent to develop random vibration standards. Although random vibration was discussed in early releases of MIL-STD-810, definition of the environment was limited by the analog vibration control technologies then available. With the advent of digital control technologies in the late 1970s, more complex random profiles could be controlled. Techniques for developing fatigue equivalent laboratory vibration specifications based on measured field data were also advancing. This led to the inclusion of the first fatigue equivalent vibration profiles in the 1983 release of MIL-STD-810D.

Single-Exciter Excitation

Until recently, the vast majority of vibration testing has been conducted on a single exciter that would impart translational motion to the test payload in a single mechanical degree of freedom (1-DOF). It also is common practice to employ appropriately phased multiple exciters on large structures to obtain 1-DOF motion. Modern exciter systems and control-system combinations can address a wide range of environmental conditions beyond the classical sinusoidal tests of years past. Consider the following examples of various environments, all of which can be addressed by modern vibration-control systems: wheeled vehicles, which tend to be dominated by predominantly low-frequency random vibrations, and aircraft and space vehicles that tend to be dominated by higher-frequency random vibrations. Combined environments such as mixed sine on random, characteristic of rotor craft or propeller-driven aircraft, and mixed narrow-band random on random, which is characteristic of tracked vehicles. While the ability to address random and combined random environments was a giant leap forward, the limitation continued of conducting vibration tests in one mechanical DOF at a time.

The limitations of 1-DOF vibration testing essentially are twofold—one of test durations and one of test fidelity. As for test duration, laboratory test times are increased due to the serial nature of addressing one DOF at a time. This approach involves not only the time required to conduct the test serially but is exacerbated by the time required to reconfigure fixturing between axes—and, in the case of testing under temperature extremes, significant additional time is associated with temperature conditioning and reconditioning. Regarding test fidelity, a 1-DOF test configuration does not allow the natural mechanical coupling of energy into the test payload across mechanical DOFs as is characteristic of the field environment. Also, in most traditional 1-DOF tests, only the translational DOFs are considered. When conducting vibration tests on gimbaled devices such as gyroscopes, that by design are intended to remain on a horizontal plane, not including the rotational motion omits a major environmental feature necessary in evaluating the device's performance.

Multiple-Exciter Test Configurations

While researchers like David O. Smallwood proposed control algorithms for MDOF random vibration as far back as the late 1970s, MDOF vibration was not formally recognized in the MIL-STD-810 until the 2008 release of MIL-STD-810G. The inclusion of the multi-exciter test, method 527, in MIL-STD-810G established a standard set of techniques and terminology essential for users and developers to improve upon the MDOF vibration test technology. Most early MDOF systems were commodity specific and often operated in an open-loop fashion. The current trend in multiple-exciter test (MET) is to design the test platform so it is generic and control is closed loop. The ability to address a multitude of payload combinations and to deal with motion combinations ranging from 1 to 6 mechanical DOFs is critical due to the upfront costs associated with MET test platforms. This is made possible through a combination of vastly improved hardware used to couple the individual actuators to the table assembly—and as a result of modern vibration control systems that can address closed-loop MDOF excitation.

Multiple-Exciter Control Options

While modern MDOF excitation systems generally are designed to be multipurpose as discussed above, they are still found in various sizes ranging from table sizes of under 100 square inches with frequency response on the order of 5 khz to large earthquake systems capable of imparting motion on entire building assemblies with a frequency response generally below 100 hz. While the smaller systems tend to be electrodynamic, the larger systems are generally servo-hydraulic. In addressing the payload sizes and frequency bandwidth of interest to many DoD payloads, the optimal test platform characteristics will often fall in between the two extremes discussed above.

Clear communication between program office and test personnel in communicating OPM/MP details is critical in the development of MDOF vibration test criteria.

Redstone Test Center MDOF System

The Army's Redstone Test Center (RTC) in Huntsville, Alabama, a subordinate of the Army Test and Evaluation Command (ATEC), recently integrated a large capacity 6-DOF (LC6-DOF) system into its Dynamic Test Division. RTC has had several years' experience in operating a pair of Team Corporations Cube Model 3 6-DOF systems. These systems performed well. However, their force rating and limited surfaces (32 inches by 32 inches) restricted payload sizes. In addressing larger payloads, the design challenge of the new system was to maintain a 500-Hz frequency response for a system with a primary moving element (table) size of 8 feet by 8 feet. The over-actuated servo-hydraulic system consists of five vertical

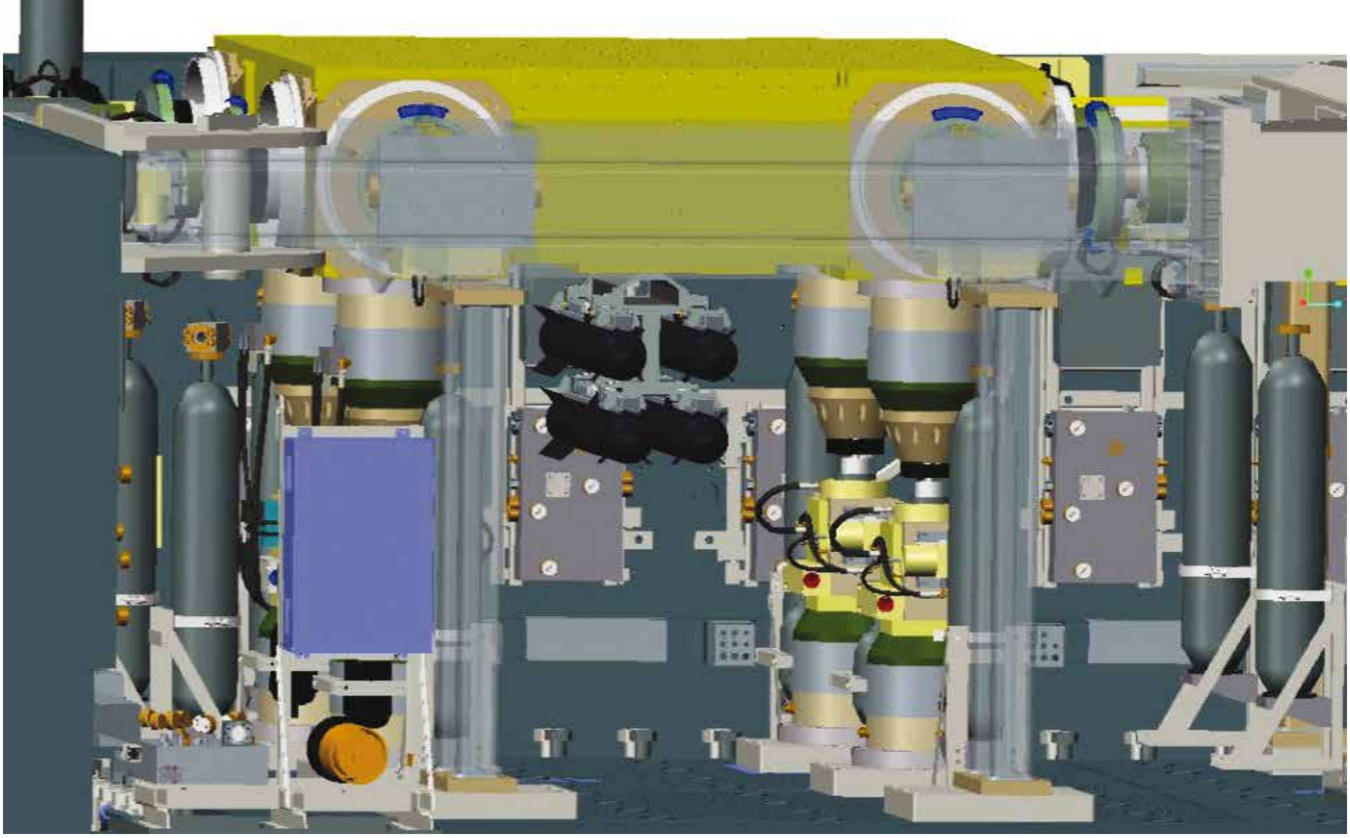
A Multiple Launch Rocket System pod mock-up illustrates a top-table mount with table extensions.
Photo by authors

and four horizontal actuators. When operating the hydraulic power supply at 3,000 pounds per square inch, the total vertical (z-axis) force rating is 225,000 pounds of force or 225 KlbF, and the horizontal (x and y axes) force ratings are 120 KlbF each. Use of high-performance pad bearing assemblies helps to minimalize the mass of the moving elements in the space-restrictive horizontal planes. Each translational DOF has a stroke capability of 3 inches double amplitude (DA) and the angular motion range is plus or minus 6 degrees about each translational axis. The first photograph is a top view of the table assembly in which 4 feet by 2.25 feet extensions have been added to the basic table assembly. Not shown in the current top-view photo is the work platform that will permit placement of a conditioning box that will encompass the table assembly and allow testing at extreme temperatures.

As described above, the LC6-DOF system is designed to be as adaptable as possible in order to address the testing needs of a wide range of military hardware, including ground and air vehicle payloads. For ground vehicle payloads, such as the Multiple Launch Rocket System pod shown in the first photo, all nine exciters are employed, with the item mounted to the top of the LC6-DOF table using tactical mounts and tiedowns to provide the most realistic vibration environment for the payload. However, for aircraft payloads suspended from a rotary wing aircraft, for example, the middle vertical actuator may be removed to enable use of a tactical launcher and bomb-rack mounted to the bottom of the LC6-DOF table for the most efficient and realistic test configuration. This option is illustrated in the second photograph. The LC6-DOF system's full performance ratings are based on a 5,000-pound payload and the ability to address multiple vibration environments. Examples of performance requirements for the LC6-DOF system at maximum load include simultaneous 3-DOF random motion as defined by the composite tactical wheeled and two-wheeled trailer environments in MIL-STD-810G-CN1, sine-on-random vibration for rotorcraft as defined in Table 514.7C-IX of 810G CN1 and various random-on-random-based tracked-vehicle environments.

MDOF Vibration Specification Development

Development of MDOF specific reference criteria and the inclusion of the MDOF criteria in military specifications are essential to the accuracy of an MDOF vibration test. As expected, this element of the MDOF vibration test lags behind the development of the laboratory test technology, but likely will see increased near-term activity. This topic is addressed in detail in the April 2014 release of MIL-STD-810G Change Notice 1. Specifically, Method 527.1—"Multiple Exciter Test," Annex E, "Laboratory Vibration Test Schedule Development for Multi-Exciter Applications"—provides the engineering and mathematical basis for establishing multiple exciter-test



Authors' model of a captive-carry payload in a bottom-table mount.
Photo by authors

reference criteria and an example for illustration purposes. As legacy programs are updated and new programs are developed, establishing well-defined laboratory vibration specifications based on the operational mode summary/ mission profile (OMS/MP) is a key programmatic element. The OMS/MP is a quantitative depiction of the wartime and peacetime usage and environmental parameters anticipated during deployment. Clear communication between program office and test personnel in communicating OPM/MP details is critical in the development of MDOF vibration test criteria. Field data acquisition efforts should be coordinated carefully and transducer placements selected so they are acceptable for development of MDOF vibration reference criteria.

Conclusions

Laboratory 6-DOF vibration systems represent the latest chapter in a long history of refining the accuracy of laboratory vibration tests. MDOF excitation and control systems continue improving and are standard equipment in many vibration test facilities. Previously limited to small payloads and low-frequency test environments, the recently completed LC6-DOF system at the Army's Redstone Test Center provides the 6-DOF vibration test capability for large military payloads with a bandwidth of 500 Hz. Lagging in the process, but expected to see more near-term activity, is development of MDOF specific reference criteria. All mechanical and control aspects of MDOF testing continue to advance, offering the rare combination of reducing test costs while improving test fidelity.

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MDAP/MAIS Program Manager Changes

With the assistance of the Office of the Secretary of Defense, *Defense AT&L* magazine publishes the names of incoming and outgoing program managers for major defense acquisition programs (MDAPs) and major automated information system (MAIS) programs. This announcement lists all such changes of leadership, for both civilian and military program managers in recent months.

Army

Michael R. Chandler relieved **Col. Robert A. Rasch** as project manager for the Integrated Air and Missile Defense (IAMD) Program on Nov. 24, 2014.

Navy/Marine Corps

Sean J. Burke relieved **Capt. James B. Hoke** as program manager for the MQ-4C Triton Program (PMA 262) on Dec. 18.

Air Force

Col. David M. Learned assumed the program manager position for the Joint Surveillance Target Attack Radar System Recapitalization (JSTARS Recap) program on Dec. 1.